Cathode Temperature Reduction By Addition Of Barium In High Power Lithium Plasma Thrusters

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Abstract. Lithium Lorentz Force Accelerators (LFA's) are capable of processing very high power levels and are therefore applicable to a wide range of challenging missions. The cathode in these coaxial discharge devices operates at a very high temperature to supply the required current and appears to be the primary life-limiting component. One potential method for lowering the cathode temperature is to add a small amount of barium to the lithium propellant. An analytical model of the surface kinetics of this system shows that a relatively small partial pressure of barium can dramatically reduce the cathode operating temperature. Preliminary experiments with a lithium-fuelled thruster demonstrated temperature reductions of 350–400 K with barium addition.

INTRODUCTION

Lorentz force accelerators are the only type of electric thruster with a demonstrated capability to process steady state power levels up to several MWe in a relatively compact device. In these engines a very high current is driven between coaxial electrodes through an alkali metal vapor or gaseous propellant. The current interacts with a self-induced or externally-generated magnetic field to produce an electromagnetic body force on the gas. LFA's can operate efficiently at power levels from 150 kWe up to tens of MWe and are therefore ideally suited for a variety of future missions requiring high power levels. The cathode, which must operate at very high temperatures and is subject to evaporative mass loss, is the primary life-limiting component. This paper describes an analytical model and preliminary feasibility experiments which show that addition of a small amount of barium to the propellant flow can dramatically reduce cathode operating temperatures.

THE CURRENT STATUS OF LITHIUM-FED LFA TECHNOLOGY

The current focus of LFA technology feasibility assessment is on applied-field, lithium-fuelled engines operating at 150–200 kWe. At these power levels the discharge current is not high enough to generate significant self magnetic fields, so an external field generated by a solenoid is used. This field induces azimuthal currents which interact with the radial and axial magnetic field components to accelerate the plasma. Lithium propellant yields very high engine efficiency because it has low frozen flow losses. Because it has a very low first ionization potential and a high second ionization potential, very little power is expended in creating the plasma. Figure 1 shows a schematic of an engine being developed by the Moscow Aviation Institute (MAI) under Jet Propulsion Laboratory sponsorship.

The electrode geometry is designed to balance engine performance considerations with lifetime concerns. The tungsten anode is designed to be radiatively-cooled for this range of power levels, and operates at a temperature of 2000 K or less. The cathode is composed of a bundle of tungsten rods enclosed in a tungsten

tube. An integral heater vaporizes the lithium propellant which then flows through the channels between rods into the discharge. These channels act as small hollow cathodes which, for the proper choice of mass flow rate and current, will very efficiently ionize the lithium. Multichannel hollow cathodes such as these offer more emitting area than comparably sized rod or single channel hollow cathodes. In addition, the attachment is more stable, the operating voltage is lower than large single channel cathodes and there is a higher probability of recapturing material evaporated from the emitting surfaces. The cathode is sized so the current density does not exceed 200 A/cm^2 of cross-sectional area (a total current of 3200 A) and operates at a temperature of about 3000 K. The main insulator between the cathode and anode in the laboratory-model

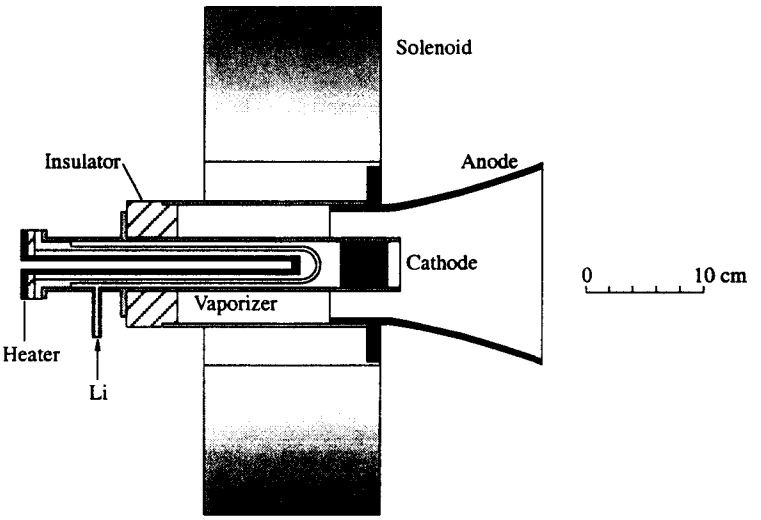

FIGURE 1. 150-200 kWe LFA Developed at the Moscow Aviation Institute.

thruster is aluminum-boron nitride, which provides sufficient life for short-term tests. Hot insulators can react with the lithium vapor, so the engine is designed to maintain a relatively low insulator temperature and isolate it from the lithium plasma. The solenoid in this engine is a water-cooled copper coil.

This engine has been operated at up to 188 kWe and has demonstrated 49 percent efficiency at an Isp of 4500 s. In relatively short duration tests performed so far, the primary life-limiting component appears to be the cathode. With proper design and operating conditions the anode and insulator are not subject to significant wear. The cathode, however, must operate at high temperatures to emit electrons and erodes primarily by evaporation, if the propellant is free of oxidizing contaminants. Erosion rates in terms of mass loss per unit charge transfer as low as 0.1–1 ng/C appear to be achievable if the current density is less than 200 A/cm^2 and the cathode is operating in the hollow cathode mode. At 3200 A, this yields a mass loss rate of 1–10 g/khr, so operation for several hundreds or perhaps a few thousand hours appears feasible. Achieving greater service life capability requires reducing the cathode operating temperature.

AN ANALYTICAL MODEL OF A CATHODE IMMERSED IN AN ACTIVATING VAPOR

The cathode operating temperature is very strongly affected by the cathode work function. Composite surfaces composed of refractory metals activated with submonolayer films of electronegative adatoms often have a work function which is lower than that of the adsorbate or the substrate. The desorption energy of submonolayer films is also generally lower than the bulk sublimation energy of the adsorbate. The work function is strongly dependent on substrate crystal orientation and coverage, and may have a deep minimum at a coverage less than one monolayer because of adatom interactions. Figure 2 shows this behavior for the work function of lithium and barium films on the (110) face of tungsten as a function of the coverage f, defined as the ratio of surface density to the density at the work function minimum, N/N_{min} (Medvedev, 1974,

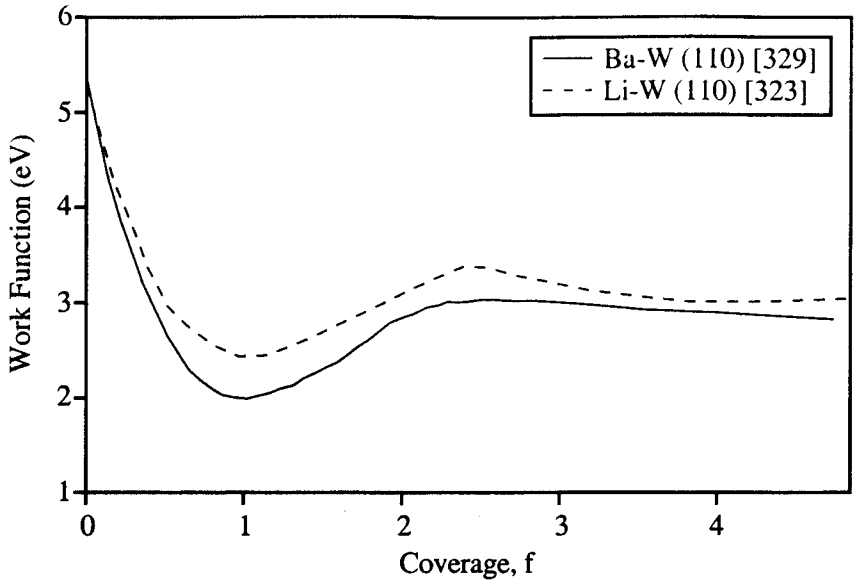

FIGURE 2. Work function of barium-tungsten and lithium-tungsten composite surfaces.

Fedorus, 1972). Because the atoms in the film desorb at cathode operating temperatures, the film material must be replenished. If a sufficient partial pressure of the activator is maintained over the emitting surface, condensation can balance the desorption rate at a given coverage level. To determine the surface emission characteristics of a tungsten cathode immersed in a lithium or barium vapor, the adsorption isotherms for these systems were modeled.

The equilibrium surface coverage of an activator j supplied to the cathode from the gas phase is given by the relationship

$$k_a^j n_{j,s} = k_d^j N_j, \tag{1}$$

where k_a^j is the condensation rate coefficient, $n_{j,s}$ is the activator gas phase number density near the surface, k_d^j is the desorption rate coefficient and N_j is the surface density. Assuming that the adsorption process is non-activated, the adsorption sites are non-localized, there are no competing adsorbate species and that the adsorbate flux to the surface is determined by the random thermal flux of vapor at a temperature equal to the surface temperature T_s, the adsorption isotherm is given by

$$\frac{P}{(2\pi m_j k T_s)^{1/2}} = \omega_j \exp(-E_d^j/kT_s) N_{min}^j f_j, \tag{2}$$

where P is the vapor pressure, m_j is the molecular weight of the activator species, k is the Boltzmann constant, ω_j is a pre-exponential constant, E_d^j is the desorption energy, N_{min}^j is the surface density at the work function minimum and f_j is the fractional surface coverage, N_j/N_{min}^j.

The adsorption of barium and lithium on tungsten appears to satisfy the first two assumptions, so this approach was used to model these systems. A tungsten surface composed of crystal faces preferentially oriented in the (110) direction was assumed because this yields the lowest work function when covered with lithium or barium. This type of surface can be achieved by chemical vapor deposition of tungsten (Hartenstine, 1994) or may result naturally from operation at high temperature because it is the lowest surface energy state (Hatsopoulos, 1979). Experimental measurements of the desorption energy and the pre-exponential factor ω for barium (Medvedev, 1969) and lithium (Medvedev, 1974) on the (110) face of tungsten as functions of coverage and temperature, respectively, are shown in Figures 3 and 4. Lithium has a lower desorption energy and a higher ω than barium, giving it a higher desorption rate for a given coverage and temperature. This is reflected in the calculated adsorption isotherms displayed in Figures 5

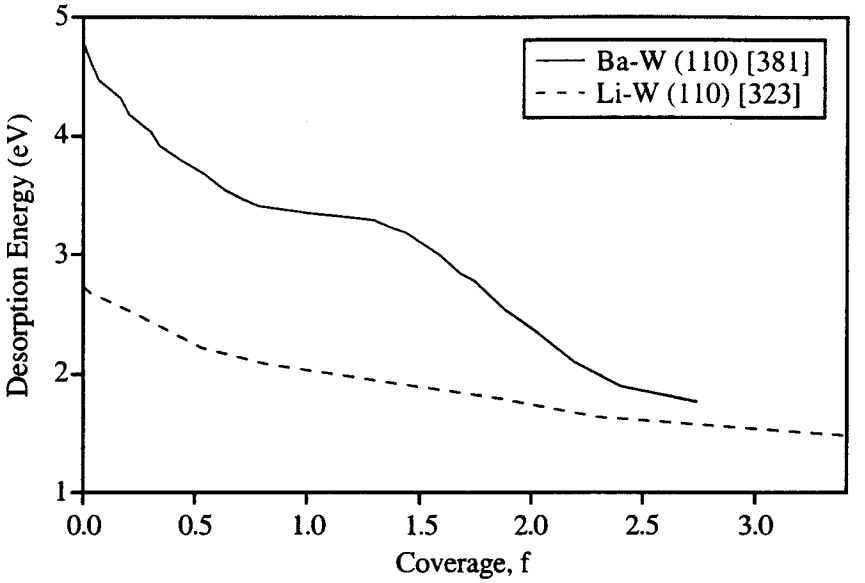

FIGURE 3. Desorption energy of barium and lithium from the tungsten (110) face.

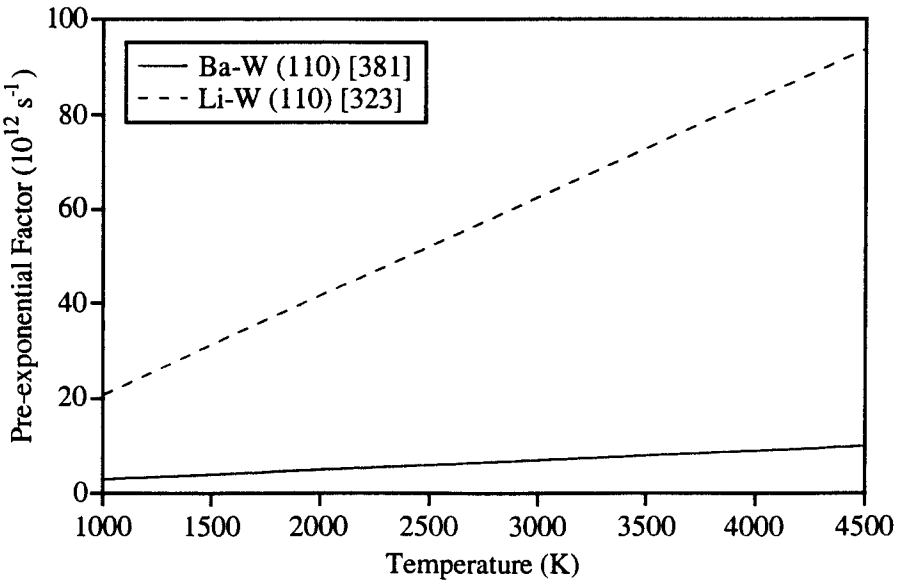

FIGURE 4. Pre-exponential factor for desorption of barium and lithium from the tungsten (110) face.

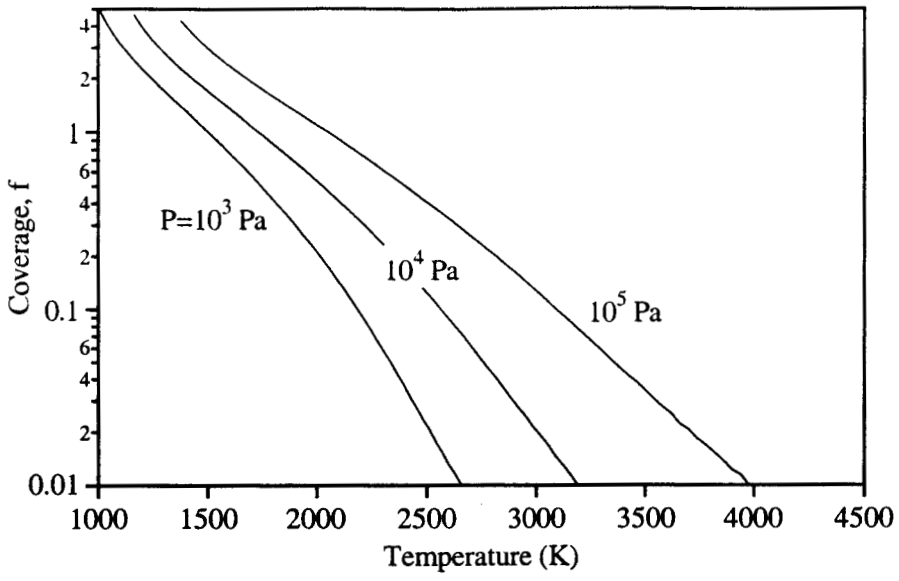

FIGURE 5. Adsorption isotherms for lithium on the tungsten (110) face.

and 6. To maintain the optimum surface coverage of lithium $f_{Li} = 1$ at a given temperature requires a vapor pressure about four orders of magnitude larger than that of barium at $f_{Ba} = 1$. These isotherms were used with the data shown in Figure 2 to calculate the work function for Ba-W and Li-W as a function of surface temperature. The minimum work function occurs at the temperature which gives the optimum coverage. At lower temperatures the work function approaches that of the bulk activator on tungsten and at high temperatures approaches that of pure tungsten. The current density calculated from the Richardson equation is plotted in Figures 7 and 8. For barium a Richardson coefficient $A = 1.5$ A/cm^{2}K^2 was used (Fomenko, 1966), and for lithium $A = 3$ was assumed. This value is equal to that of cesium on tungsten, a more well-characterized alkali metal-tungsten system. As the coverage approaches zero or many monolayers, the value of A should approach 120 A/cm^{2}K^2, the theoretical value for pure metals. The current density for pure tungsten, lithium and barium are plotted in these figures as well, showing that the calculated S-curves for the composite surfaces underestimate the current density at low and high temperatures because of the assumed Richardson coefficient.

These calculations show that to extract high current densities from a cathode immersed in a lithium vapor requires unreasonably high lithium partial pressures. Evidently decreased cathode operating temperatures measured with lithium propellant are due to simultaneous adsorption of lithium and oxygen present as an impurity in the lithium (Babkin, 1979). Such surfaces have a lower work function minimum than lithium alone on tungsten and may also elevate the lithium desorption energy. Unfortunately, the oxygen impurities also cause chemical erosion of the tungsten, apparently negating the lifetime gains associated with the lower temperature. However, barium can be used as a propellant additive to maintain a low work function with quite reasonable partial pressures. Comparing the pure tungsten curve with the activated surface curves suggests that temperature reductions of over 1000 K should be possible.

PRELIMINARY EXPERIMENTS WITH BARIUM ADDITION

In tests of this approach using barium vapor added to the lithium propellant vapor in a high power LFA a temperature reduction of over 1000 K was reported (Ageyev, 1993). Similar experiments were performed at MAI with a 30 kW lithium plasma thruster to verify these findings. This thruster is similar in design to that shown in Figure 1 and operates at current levels of 600–700 A with an efficiency of up to 32 percent at Isp's as high as 3600 s (Tikhonov, 1993). A small tungsten cup filled with barium metal and capped with

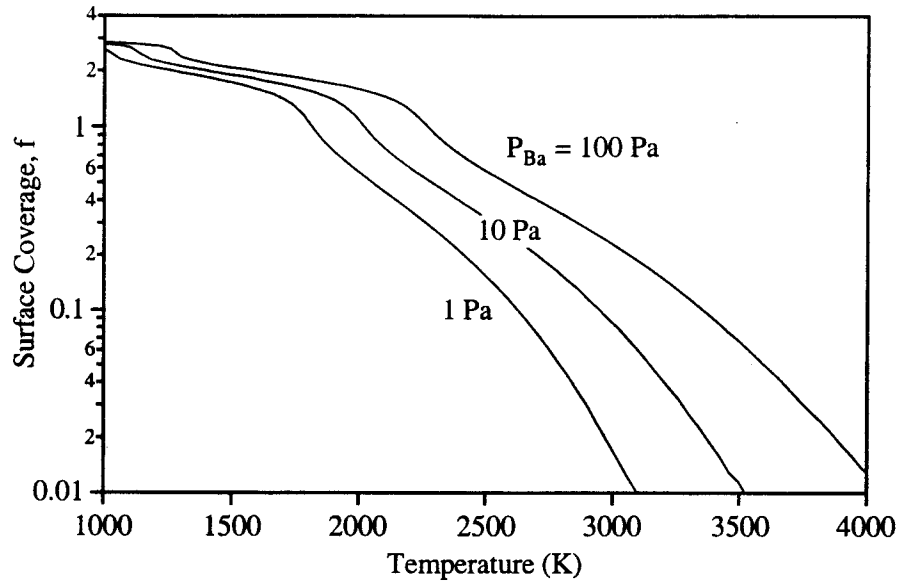

FIGURE 6. Adsorption isotherms for barium from the tungsten (110) face.

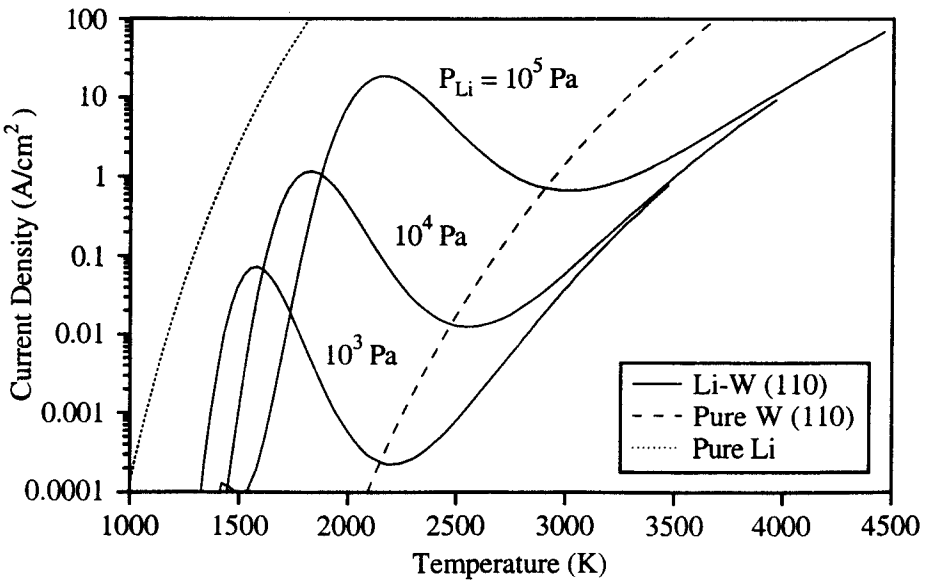

FIGURE 7. S-curves of emission current density for the lithium-tungsten (110) system.

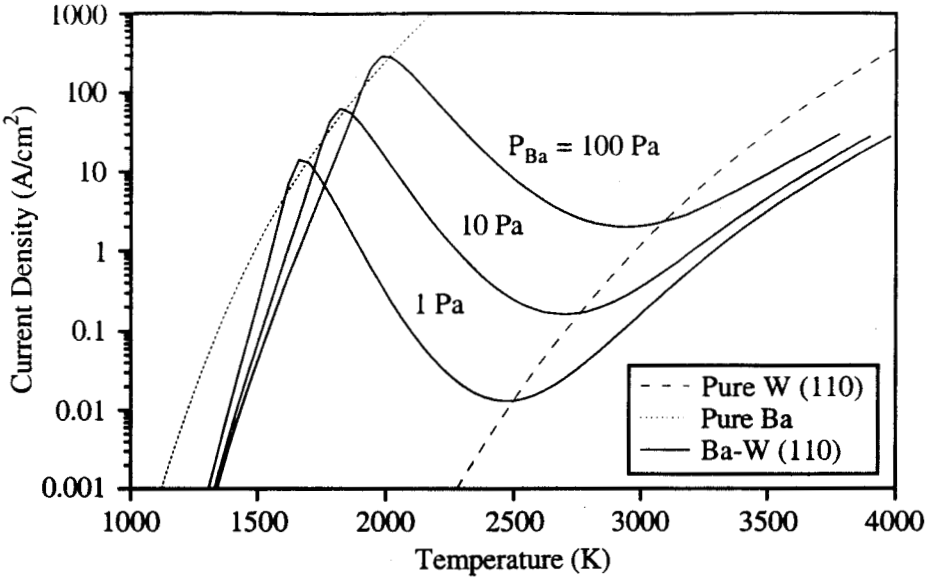

FIGURE 8. S-curves of emission current density for the barium-tungsten (110) system.

a porous tungsten plug was placed inside the cathode tube upstream of the tungsten rods. As this cup was heated by operation of the discharge, barium vapor was released into the lithium propellant flow.

In these preliminary experiments there was no way to control or measure the barium flow rate, and the only possible location for the barium source in this thruster design was near the tip of the cathode where the temperatures were 1500–1700 K. This resulted in very high initial partial pressures of barium during the first few minutes of operation. During this phase of operation the discharge was characterized by low discharge currents I_d and increased values of the discharge voltage V_d. All attempts to raise the discharge current resulted in further increases in discharge voltage with an almost constant discharge current. In each experiment the thruster transitioned to a normal operating mode which most likely corresponded to a lower, more stable barium flow as the supply in the source was depleted. During this phase the thrust T was measured using the apparatus described in (Tikhonov, 1995) and cathode and anode temperatures T_c and T_a were measured with an EOP-66 optical pyrometer. Table 1 compares results obtained with and without barium addition at similar lithium flow rates $\dot{m}$, applied magnetic field strength measured at the cathode tip B_c and discharge current.

TABLE 1. Comparison of thruster operation with and without barium addition.

Mode	$\dot{m}$ (mg/s)	B_c (G)	I_d (A)	U_d (V)	T (N)	η	T_c (K)	T_a (K)
Li + Ba	14.0	1000	700	38.0	0.499	0.335	2513	2153
Li	13.5	1000	700	41.5	0.504	0.325	2903	2273

The experimental results show unambiguously that the addition of barium results in a cathode temperature reduction of 350–400 K and an anode temperature reduction of about 100 K with no significant change in thruster performance.

CONCLUSIONS

The analytical model of activator adsorption and work function lowering on tungsten suggests that substantial cathode temperature reductions are possible with barium addition. Preliminary experiments with an uncontrolled lithium vapor flow qualitatively confirm these predictions. A cathode with a geometry, thermal

design and barium vapor flow rate optimized to operate at the minimum work function should be capable of running at a temperature of 2000–2500 K for many thousands of hours. Subsequent work will focus on modeling the effect of the electric field on the transport of lithium and barium ions in the cathode concentration boundary layer and performing experiments with controlled flow rates of barium to determine the optimum operating conditions.

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